METHODS OF CONTACT STRESSES MEASUREMENT OVER SURFACES OF A CUTTER

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Abstract. The paper presents methods of contact stresses measurement over surfaces of cutter. Distribution of contact loads over a face and a flank surfaces of a cutter can be investigated experimentally by three methods: 1) by the optical polarization method, 2) by the method of interference, 3) by the method of a “split cutting tool”. The method of a “split cutting tool” is more preferable for research in cutting steels and strong materials with real cutting mode. Research of distribution of contact loads (stresses) over surfaces of a cutter it is necessary to carry out on the special rigid four-component dynamometer for a “split cutter” with inspection of total component of cutting force Pz and Py. But investigation of contact loads distribution over a flank-land faces the problem due to elastic deformation of measuring elements and penetration of worked material into the slit between two parts of the “split cutter”. Research of distribution of contact loads over a face of a cutter it is necessary to carry out on a lathe with horizontal feed f, but research of distribution of contact loads over a flank-land – on a horizontal-milling machine with vertical feed f of a table. Distributions of contact loads over the flank-land of the cutter in turning of ductile brass (63Cu37Zn) and brittle brass (57Cu16Zn1Al3Mn) are described. In machining of ductile brass extreme pattern of normal σ_h and tangential τ_h specific contact loads curves is observed, i.e. the highest normal contact load $\sigma_{h\,max}$ is at some distance from the cutting edge. In machining of brittle brass the highest normal and tangential specific contact loads is observed, in the contrary, near the cutting edge. Character of normal contact loads over a flank-land depends on the type of the chip formation due to a sag of the transient surface under the radial component of the cutting force on the rake surface.

1. Introduction

In machining of difficult-to-machine titanium alloys, brittle fracture of the cutting wedge occurs in the form of chipping and spalling, which is especially dangerous for indexable inserts made from commonly used in industry cemented carbides. Increasing of wear of cutting tools leads to increasing of cutting force and chipping and spalling of cutting wedge. The wear of cutting tool is the wear of the cutting wedge, and takes place: 1) on the face near the cutting edge, 2) on the cutting edge with appearance of radius ρ of cutting edge, 3) on the flank with appearance of flank-land with length h_f and clearance angle α_h (Figure 1). Very often clearance angle α_h is equal to zero.

Calculation of cutting tool strength requires knowledge about distribution of contact loads (external stresses or specific loads) over a face and a flank

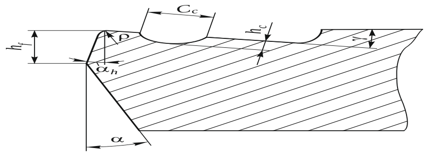

Figure 1. Cutting wedge wear

surfaces of a wedge. They can be investigated experimentally by three methods: 1) by the optical polarization method [1, 2, 3, 4], 2) by the method of interference [1], 3) by the method of a “split cutting tool” [1, 2, 4].

The method of a “split cutting tool” allows to research distribution of contact loads (external stresses) with industrial cutting mode, but one demands creation of rigid dynamometer [1, 4]. In order to be sure about constant condition during experiments it is necessary to measure total components of cutting force: tangential component Pz and radial component Py [1]. They must be constant does not looking what area of cutting edge of the “split cutter” now in the contact relatively machined workpiece (very often it is a disk which is machined with radial feed rate *f* for realization of free orthogonal cutting) (Figure 2).

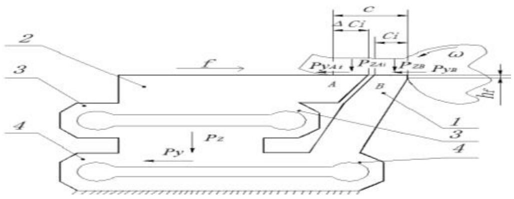

Figure 2. The research of contact loads distribution over a face surface of the cutting tool by the method of the “split cutter” on a lathe with horizontal feed rate f

Construction of dynamometer contains lower level of elastic measuring elements 4, which are used for measurement and inspection of total components of cutting force Pz and Py – they have to be constant during serial of experiments. These forces are large and thickness of walls are large – measuring elements 4 are more rigid in comparison with upper elastic measuring elements 3 [1].

Upper level of elastic measuring elements 3 is used for measurement of force components Pz_A and Py_A which act on the surface of part A of the “split cutter”. The “split cutter” consists of two parts: part B with face surface, cutting edge and flank surface and part A which is used for measurement forces Pz_A and Py_A on the face of cutter – it is the main plate of the “split cutter”. This dynamometer is named as “four-component dynamometer for a split cutter” [1].

Consistent displacement of the dynamometer with the “split cutter” along periphery of the disk and cutting the disk with radial feed f allows to increase area of a surface with length ΔC_i of the plate A. Specific contact loads are calculated as a ratio of an increment of forces over the plate A to an increment of area of this surface.

2. Research methods

Cutting plates, A and B are fabricated so that distance C_B from the cutting edge to a slanting slit (clearance) with an angle ψ_B between plates is more length of contact *c* of a chip with a face surface of the cutter ($C_B > c$) (Figure 3). The less size C_B and larger length of plates the less the angle ψ_B and more accuracy of contact loads calculation. Dynamometer, used in our experiments, allows to mount long plates with length 100 mm.

In a kickoff a machined disk is placed in the position 0 (i=0) where there is no contact of the chip with the plate A. In the Figure 3 it is the upper part of the plate B with the length c and with the width b_c of the chip contact with the face surface of the cutter. In this case on the plate A forces of cutting will be equal to zero: $Pz_{A\,i=0} = 0$ [N] and $Py_{A\,i=0} = 0$ [N]. For the free orthogonal cutting and for the rake angle γ=0º $Pz_{Ai} = N_{Ai}$, $Py_{Ai} = F_{Ai}$.

In free orthogonal cutting the disk we consistently displace the dynamometer with the cutter along periphery of the disk on the length l_i relatively the position 0 (Figure 3), cut the disk and measure force components $Pz_{A\,i}$ and $Py_{A\,i}$ (Figure 2).

The increment of the surface area for position 2 (i+1) relatively the previous position 1 (i) occurs on the length $\Delta C'_2 = \Delta C_2 - \Delta C_1$. In the general form this increment of the length is $\Delta C'_{i+1} = \Delta C_{i+1} - \Delta C_i$.

The increment of the normal force over this area with length $\Delta C'_2$ is calculated by the formula $\Delta N'_{A\,2} = N_{A\,2} - N_{A\,1}$, or in the general form $\Delta N'_{A\,i+1} = N_{A\,i+1} - N_{A\,i}$, i.e. force on the plate A for the considered position minus force for the previous position. Also for the tangential force $\Delta F'_{A\,i+1} = F_{A\,i+1} - F_{A\,i}$.

The ratio of these forces increment to the contact area increment is the specific normal and tangential cutting force over the increment of zone (i+1) (with the length $\Delta C'_{i+1}$). For the rake angle γ=0º:

$$q_{N'\,i+1} = \Delta N'_{A\,i+1} / (\Delta C'_{i+1} \cdot b_c); \; q_{F'\,i+1} = \Delta F'_{A\,i+1} / (\Delta C'_{i+1} \cdot b_c).$$

For very small displacement of the dynamometer along the disk periphery ($\Delta l_i \rightarrow 0$, where $\Delta l_{i+1} = l_{i+1} - l_i$) the increment of contact length of the chip over the plate A $\Delta C'_{i+1}$ will be small ($\Delta C'_{i+1} \rightarrow 0$), the area increment will be small, therefore the specific normal force $q_{N'\,i+1}$ over this area will be considered as a normal stress over rake surface σ ($\sigma_{i+1} \approx q_{N'\,i+1}$). Similarly for a shearing stress τ ($\tau_{i+1} \approx q_{F'\,i+1}$).

Use of lower level of elastic measuring elements 4 (Figure 2) permits to avoid penetration of the chip into the slit between plate A and B. Construction of four-component dynamometer for the “split cutter” foresees less rigidity of elements 3 in comparison with elements 4 in order to be more sensitive as forces Pz_A and Py_A less then forces Pz_B and Py_B.

Forces Pz_B and Py_B act on the plate B over face and flank surfaces of this plate (Figure 2). Elements 4 are deformed elastically and are shifted slightly lower

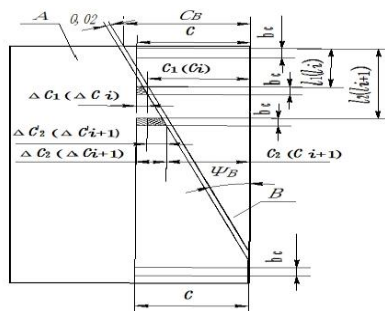

Figure 3. The research scheme of contact loads measurement over the face surface of the cutter by the method of the “split cutter”

and in the left direction (out from workpiece) together with the elements 3, which are mounted on the lower level of elastic measuring elements 4. Exceeding (projection) of the plate A relatively the plate B is not formed. Forces $Pz_{A\,i}$ and $Py_{A\,i}$ act on the plate A and deform elastically the measuring elements 4 relatively the plate B, the plate A is shifted slightly lower and in the left direction (out from plate B). Projection of plate A relatively the plate B is not formed.

Research of contact load distributions over the flank-land with use of above scheme of cutting faces a problem of elastic deformation of measuring elements 3 (Figures 4).

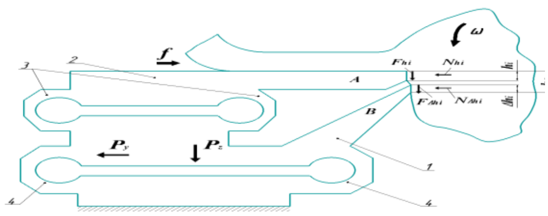

Figure 4. The research scheme of contact loads distribution over the flank-land of the cutting tool by the method of the “split cutter” on a lathe with horizontal feed rate f

The force $Py_{A\,i}$ ($Py_{A\,i} = Py_{A\,face} + N_{h\,i}$) acts on the plate A and slightly displaces the plate A in the left direction (out from plate B) due to small rigidity of element 3, that leads occurrence exceeding the plate B relatively the plate A. The sharp projection of the plate B starts to cut off an additional chip from the surface of the disk. The slit between plates A and B is hammered that leads to violation of forces measurement and even to breakage of plates.

For elimination of the specified undesirable phenomena it is necessary to change the cutting scheme. Research of contact loads over the flank surface is necessary to carry out on a horizontal milling machine with the vertical feed f of machine tool table (Figure 5).

Forces Pz_B and Py_B act on the plate B over the face and some part of the flank-land surface of this plate. Elements 4 are deformed elastically and are shifted slightly lower and in the left direction (out from workpiece) together with elements 3, which are mounted on the lower level of elastic measuring elements 4. Exceeding plate A relatively plate B is not formed.

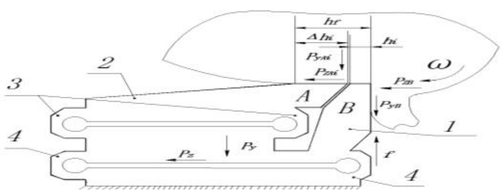

Figure 5. The research scheme of contact loads distribution over the flank-land of the cutting tool by the method of the “split cutter” on a horizontal-milling machine with vertical feed rate f of a table

Force $Py_{A\,i}$ act on the plate A over an area with length Δh_i ($\Delta h_i = h_f - h_i$) of the flank-land and displaces plate A slightly lower than plate B due to small rigidity of elements 3. Exceeding plate A relatively plate B is not formed due to large rigidity of elements 4.

For this scheme of cutting plates A and B are fabricated so that distance C_B from the cutting edge to the slanting slit with an angle ψ_B between plates is more the length of flank-land h_f of the cutter ($C_B > h_f$) (Figure 6).

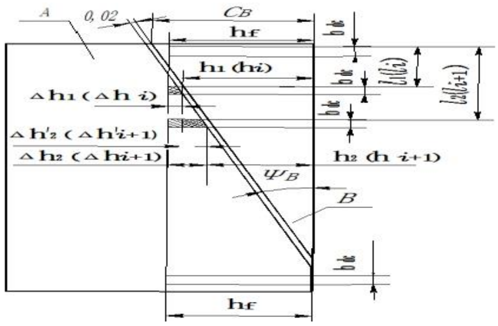

Figure 6. The research scheme of contact loads measurement over the flank-land of the cutter by the method of the “split cutter”

In a kickoff the disk is placed in the position 0, where there is no contact of the disk with the plate A. In the Figure 6 it is the upper part of the plate B with length h_f of flank-land and with the width b_{dc} of the disk contact with the disk. In this case on the plate A forces of cutting are equal to zero.

We consistently displace the dynamometer with the cutter along periphery of the disk, cut the disk and measure force components $Pz_{A\,i}$ and $Py_{A\,i}$ (Figure 5). For clearance angle of the flank-land $\alpha_h = 0°$ Py_{Ai} is equal to the normal force over the flank-land of the plate A with length Δh_i, i.e. $N_{hAi} = Py_{Ai}$. The same is for the tangential force: $F_{hAi} = Pz_{Ai}$.

The increment of the area of position (i+1) relatively the previous position (i) occurs on the length $\Delta h'_{i+1} = \Delta h_{i+1} - \Delta h_i$.

The ratio of forces increment $\Delta N'_{A\,i+1}$ and $\Delta F'_{A\,i+1}$ to the contact area increment is a specific normal and tangential cutting force over the area with the length $\Delta h'_{i+1}$:

$$q_{N'h\,i+1} = \Delta N'_{A\,i+1} / (\Delta h'_{i+1} \cdot b_{dc}) = \Delta P'y_{A\,i+1} / (\Delta h'_{i+1} \cdot b_{dc});$$

$$q_{F'h\,i+1} = \Delta F'_{A\,i+1} / (\Delta h'_{i+1} \cdot b_{dc}) = \Delta P'z_{A\,i+1} / (\Delta h'_{i+1} \cdot b_{dc}).$$

For very small displacement of the dynamometer along disk periphery ($\Delta l_{i+1} \to 0$) the area increment will be small, therefore specific normal force $q_{N'h'\,i+1}$ over flank-land in this position will be considered as a normal stress σ_h ($\sigma_{h'\,i+1} \approx q_{N'h\,i+1}$). Similarly for a shearing stress over this area of the flank-land τ_h ($\tau_{h'\,i+1} \approx q_{F'h\,i+1}$).

The slit between plates A and B is inspected by a blade with the thickness 0.02 mm. Small clearance leads to contact of plates and violation of forces measurement that is registered by reducing of the force $Py_{A\,i}$. Large clearance leads to penetration of additional chip in the slit between plates A and B that leads to chipping of working plates and to change of cutting force components Py and Pz. Absence of contact of plates is inspected also on a gleam during experiment.

3. Preparation for experimental study of contact load distribution

Experiments were carried out in free orthogonal turning of a disk made from workpiece material and with the radial feed *f* of a cutter (for research of contact load distributions over the rake surface by means horizontal feed on the lathe, over the flank surface – by means vertical feed f of the table on the horizontal-milling machine). The ductile brass (63Cu37Zn), which forms continuous chip and the brittle brass (57Cu1Al3Mn), which forms discontinuous chip, were used as workpiece material. Brass was selected to fine-tune the method of a split cutter.

Wear was simulated by sharpening a chamfer with a length h_f on a flank surface ground with the clearance angle $\alpha_h = 0$ º. The length h_f of the artificial flank-land was measured by means of a toolmaker’s microscope.

The width of contact b_c and b_{dc} was accepted equal to the width of a disk $b_d = 4$ mm. The focus was given to experimental research of contact loads distribution on a flat section of an artificial flank-land, which was used to simulate flank wear.

4. Results of experiments and dicusiion

In machining of ductile brass (63Cu37Zn) by the “split cutter” with length of the artificial flank-land $h_f = 2.4$ mm and clearance angle $\alpha_h = 0$ º extreme pattern of σ_h curves over flank-land is observed, i.e. the highest normal contact load $\sigma_{h\,max}$ is at some distance from the cutting edge (Figures 7 and 8).

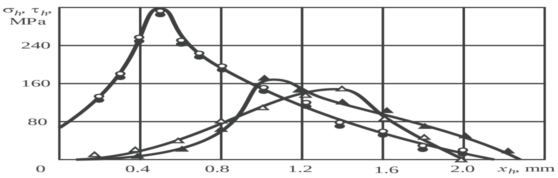

Figure 7. Distribution of contact stresses on the flank-land of the cutter in ductile brass (63Cu37Zn) machining. $\gamma = 0$ º, $\alpha = 18$ º, $\alpha_h = 0$ º, v =1.7 m/s, ○, ● – f = 0.06 mm/r; Δ, ▲ – f = 0.21 mm/r; ○, Δ – normal contact load σ_h; ●, ▲ – tangential contact load τ_h. Ordinate – normal σ_h [MPa] and tangential τ_h [MPa] stresses over the flank-land; abscissa – distance from the cutting edge over the surface of the flank-land x_h [mm]

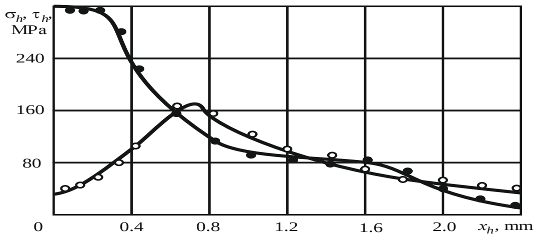

Figure 8. Distribution of contact stresses on the flank-land of the cutter in cutting of ductile brass (63Cu37Zn). $\gamma = 0$ º, $\alpha = 18$ º, $\alpha_h = 0$ º, $v = 3.6$ m/s, $f = 0.21$mm/r; ○ – normal contact load σ_h; ● – tangential contact load τ_h.

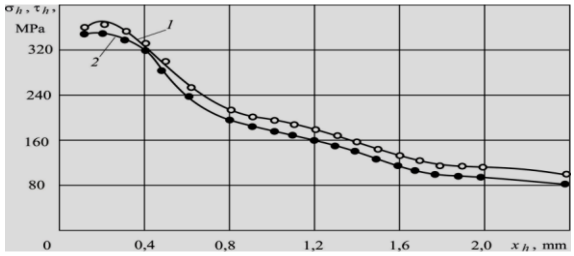

Figure 9. Distribution of normal σ_h (○) and tangential τ_h (●) contact stresses on the flank-land of the cutter in cutting of brittle brass (57Cu1Al3Mn). $\gamma = 0$ º, $\alpha = 18$ º, $\alpha_h = 0$ º, v=1.7 m/s, f =0.41 mm/r.

In machining of brittle brass (57Cu1Al3Mn) by a cutter with the same geometry and cutting speed, the highest contact load $\sigma_{h\ max}$ is near the cutting edge (Figure 9).

Extreme pattern of curves of normal σ_h and tangential τ_h specific contact loads over flank-land in machining of ductile materials was also mentioned by the other researches [4], however authors have not discovered explanations of this phenomenon.

In our opinion, the highest normal contact loads σ_h in cutting with continuous chip are at some distance from a cutting edge due to a sag of the transient surface under the radial component of the cutting force on the rake surface $P_{y\ r}$ [7].

In continuous chip formation the influence of radial component of the cutting force $P_{y\ r}$ on the face is stable [8], a sag of the transient surface is constant, therefore, pressure from the elastic recovering transient surface on the flank-land is higher at some distance from cutting edge (Figures 7 and 8).

During discontinuous chip formation at the moment when formed chip elements separate from the workpiece, the radial component of the cutting force on the face $P_{y\ r}$ quickly decreases (sometimes to zero) [8], which leads to elastic recovery of the transient surface and its pressure upon the cutting tool flank surface. To a greater degree this pressure acts near the cutting edge [7], therefore the highest normal contact load $\sigma_{h\ max}$ is observed near the cutting edge, which is confirmed by results of experiments in machining of brittle brass (57Cu1Al3Mn), which forms discontinuous chip (Figure 9).

In machining of brass, tangential contact loads τ_h are equal to normal ones σ_h (Figures 7), except for the case of ductile brass (63Cu37Zn) machining at elevated cutting speed v = 3.62 m/s, when the highest value of $\tau_{h\ max}$ is observed near the cutting edge, where it is not equal to normal contact loads σ_h (Figure 8).

Equality of tangential and normal contact loads is associated, in our opinion, with plastic character of contact on the flank-land. The high coefficient of friction $\mu = \tau_h / \sigma_h \approx 1$ does not correspond to usual external friction, when coefficient of friction is equal to 0.15 … 0.1. In case of plastic contact, the tangential contact loads τ_h cannot be calculated by the formula $\tau_h = \sigma_h \times \mu$, as they will be equal to shear strength of a material τ_{max} at the operating temperature in the contact zone ($\tau_h = \tau_{max}$) [5, 6].

At elevated cutting speed v = 3.6 m/s (Figures 8), the higher temperature of cutting promotes adhesion of contact surfaces, thus strong seizure takes place even at insignificant pressure ($\sigma_h \approx 40$ MPa), what was observed near the cutting edge. High value of $\tau_{h\ max}$ = 320 MPa is explained, in our opinion, by increased strain rate and hardening of work material. Softening of the work material due to influence of temperature at increased cutting speed doesn’t have time to occur [9, 10, 11].

5. Conclusion

1. Research contact stresses distribution over surfaces of a cutter is necessary to carry out on the special rigid four-component dynamometer for a “split cutter” with inspection of total component of cutting force Pz and Py – they have to be constant during serial of experiments.

2. Research contact loads over a face of a cutter with the help of special four-component dynamometer for a “split cutter” is necessary to carry out on a lathe with horizontal feed f, but research of contact loads over a flank-land – on a horizontal-milling machine with vertical feed f of a table.

3. Character of normal contact loads over a flank-land depends on the type of the chip formation due to a sag of the transient surface under the radial component of the cutting force on the rake surface.

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